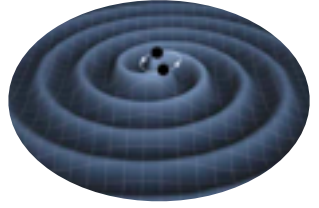


The Science of Gravitational Waves with Space Observatories

J.I.Thorpe

NASA Goddard Space Flight Center

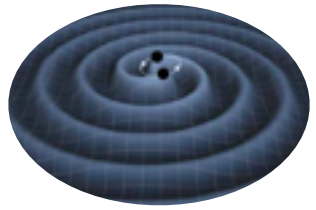


Talk Outline

- I. Gravitational Waves - What, Where, Why, & How?
- II. The “classic” LISA mission
- III. Science with LISA
- IV. Current concepts & opportunities

Gravitational Waves

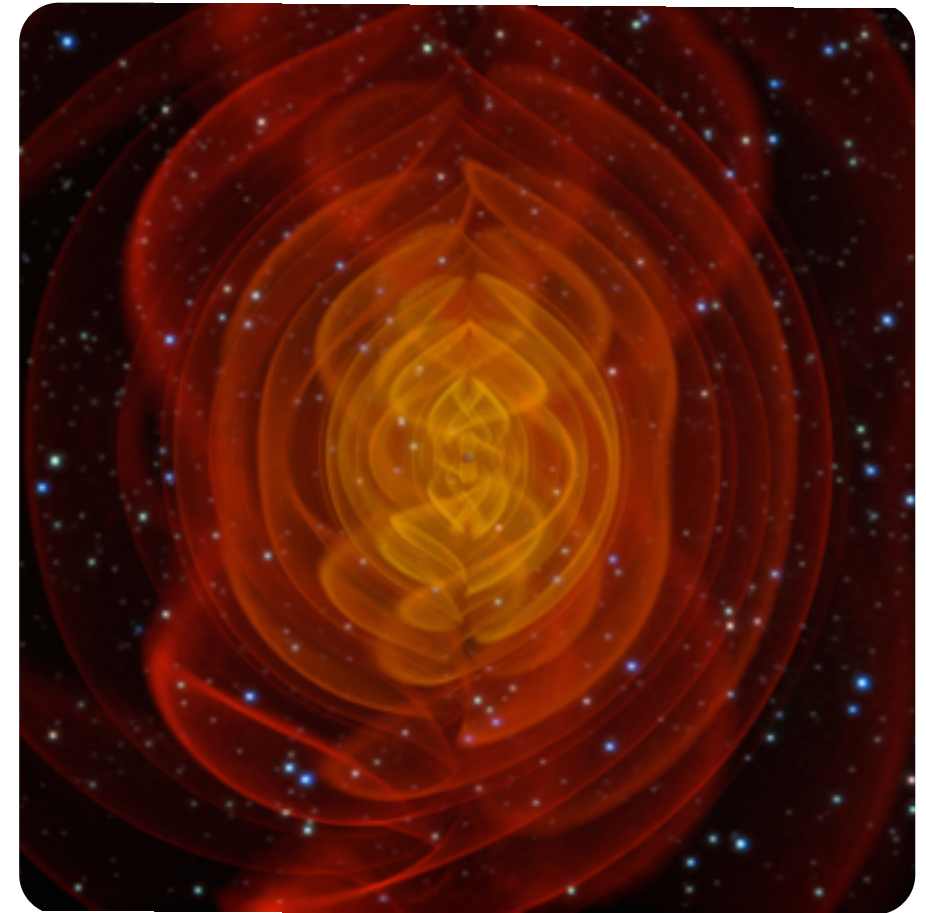
what?
where?
how?
why?

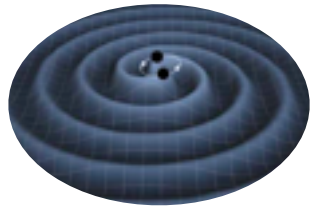


What are Gravitational Waves?

Dynamical part of spacetime

- Wave solutions to vacuum Einstein equations
- curvature perturbations to background metric
- Propagate at the speed of light
- carry energy & momentum
- have two polarizations



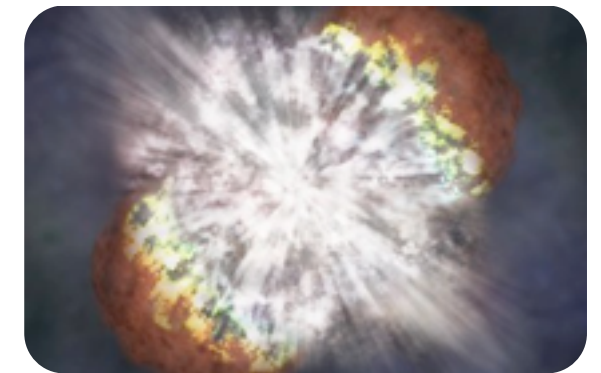
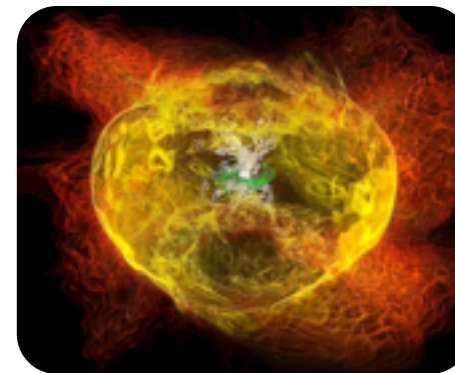


Where do they come from?

$$L_{GW} \propto \frac{M^2 v^6}{r^2}$$

↖ large masses
↖ high velocities
↖ small volumes

Formation of compact objects



Compact objects in binaries

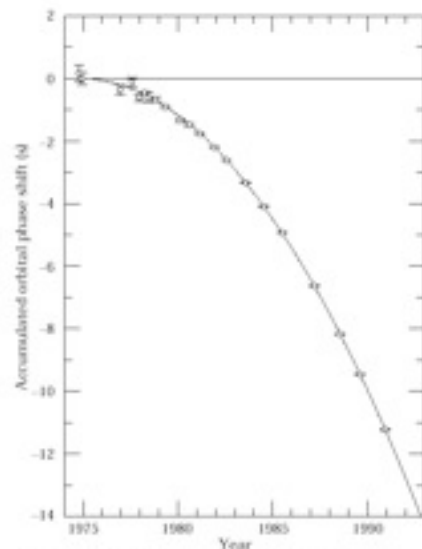
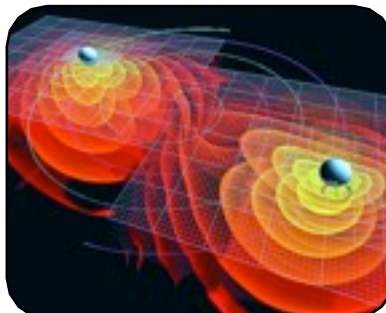
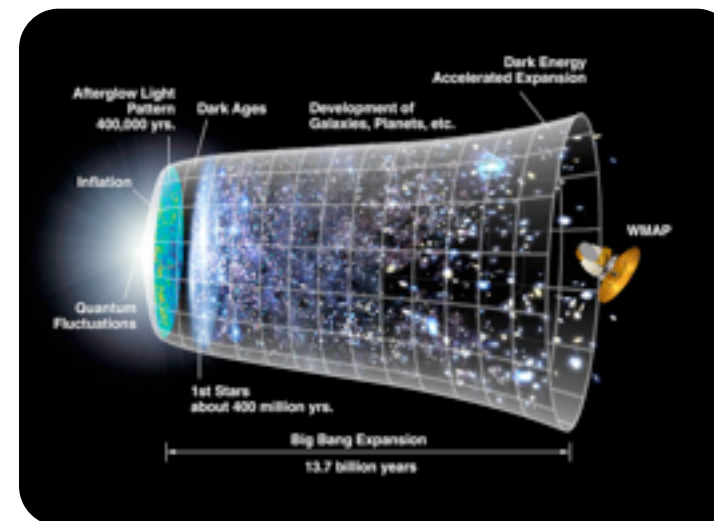
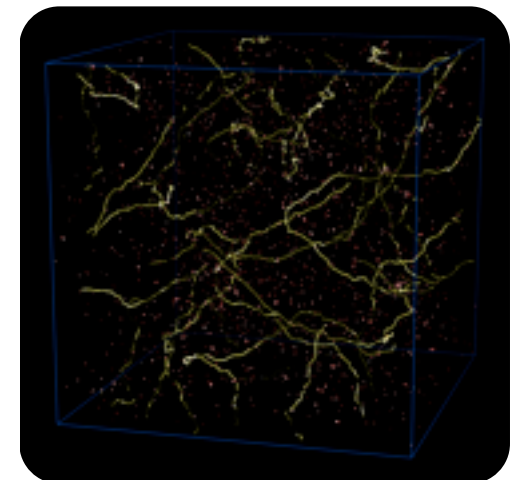


Figure 14.1: Accumulated shift of the times of periastron passage in the PSR 1513-16 system, relative to an assumed orbit with a constant period. The possible curve represents the general relativistic prediction, modified by Galactic effects, for orbital period decay from gravitational radiation damping forces.

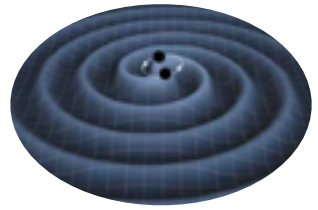
Big Bang



Cosmic Strings?

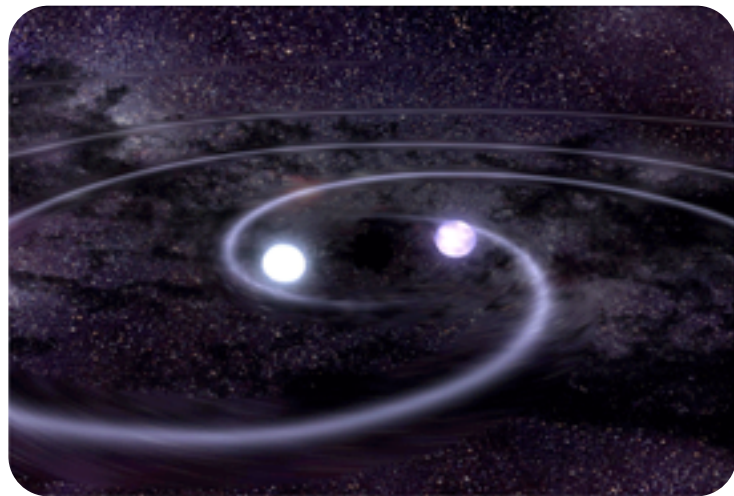


LBNL



Binary inspirals & merger

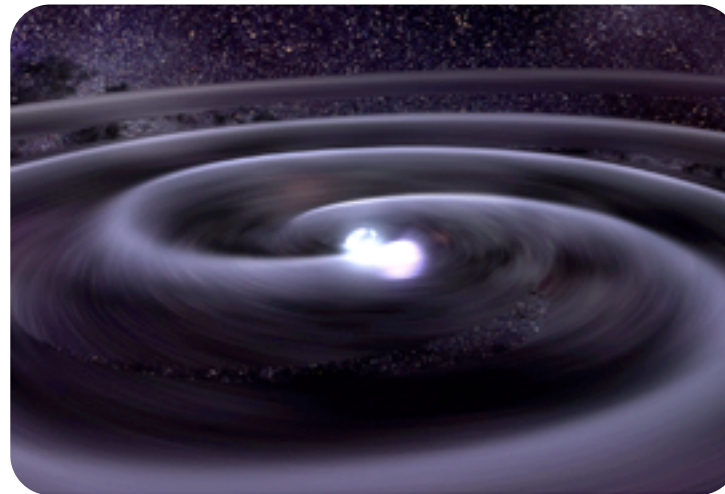
Early Inspiral



- GWs carry away energy
- Adiabatic shrinking of the binary
- Analytically tractable

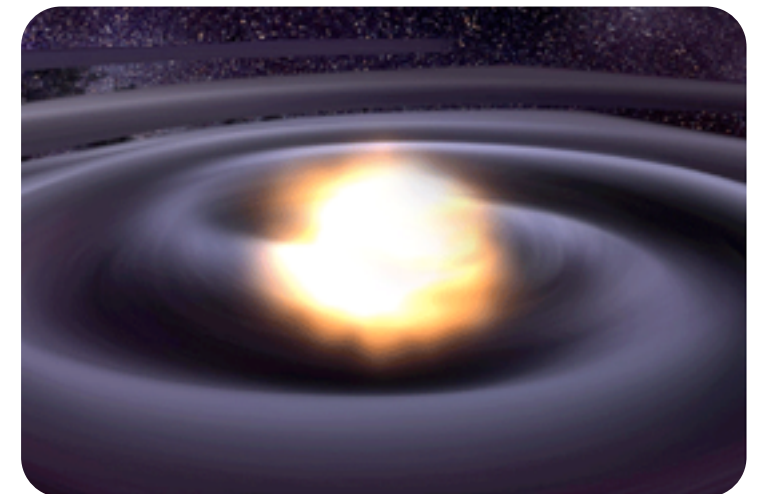
$$a(t) = a_0 (1 - t/\tau)^{1/4}$$

Late Inspiral

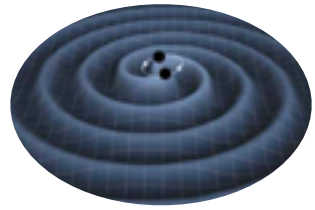


- exponential increase in L
- More complex physics
 - GR orbital effects
 - tides & mass-transfer

Merger



- merger of compact object(s)
- formation of new object
- physics more difficult



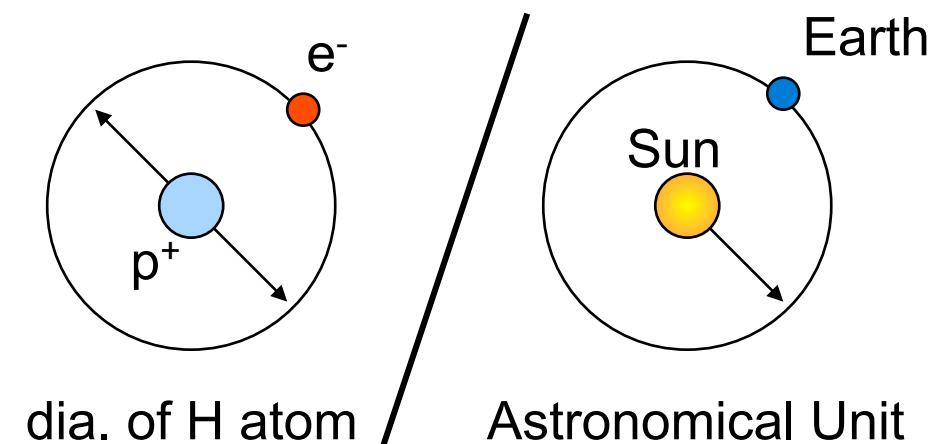
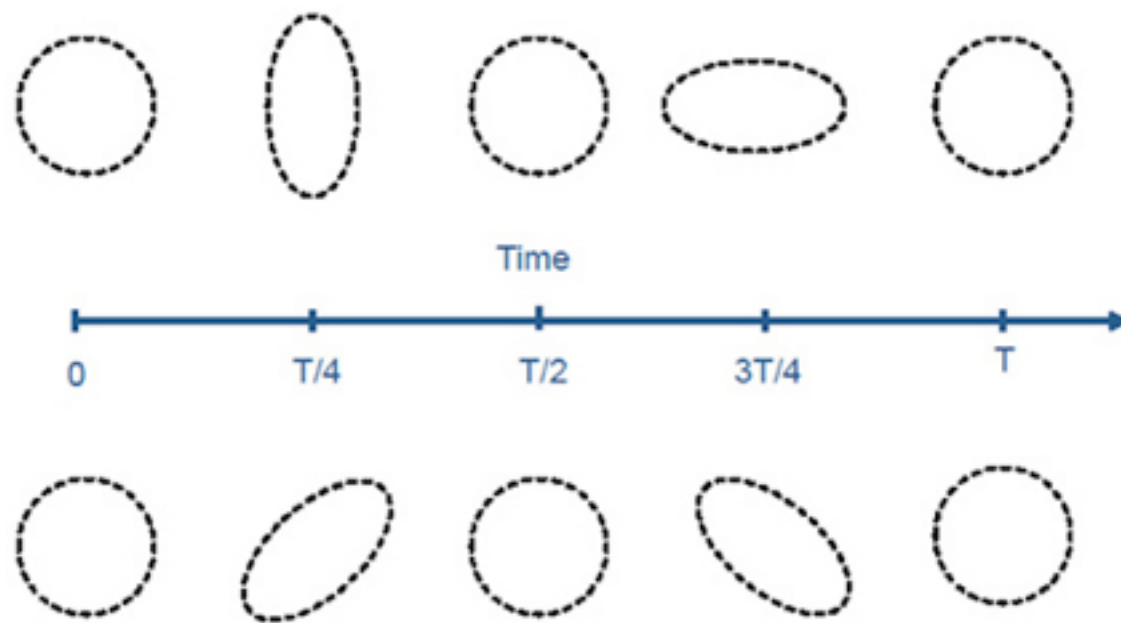
Detecting Gravitational Waves

- Oscillating tidal distortions
- Displacement scales with separation
- Two polarizations

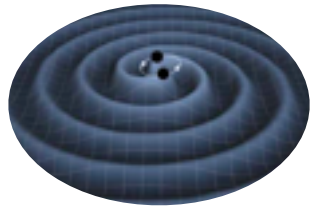
small amplitudes

linear in source distance

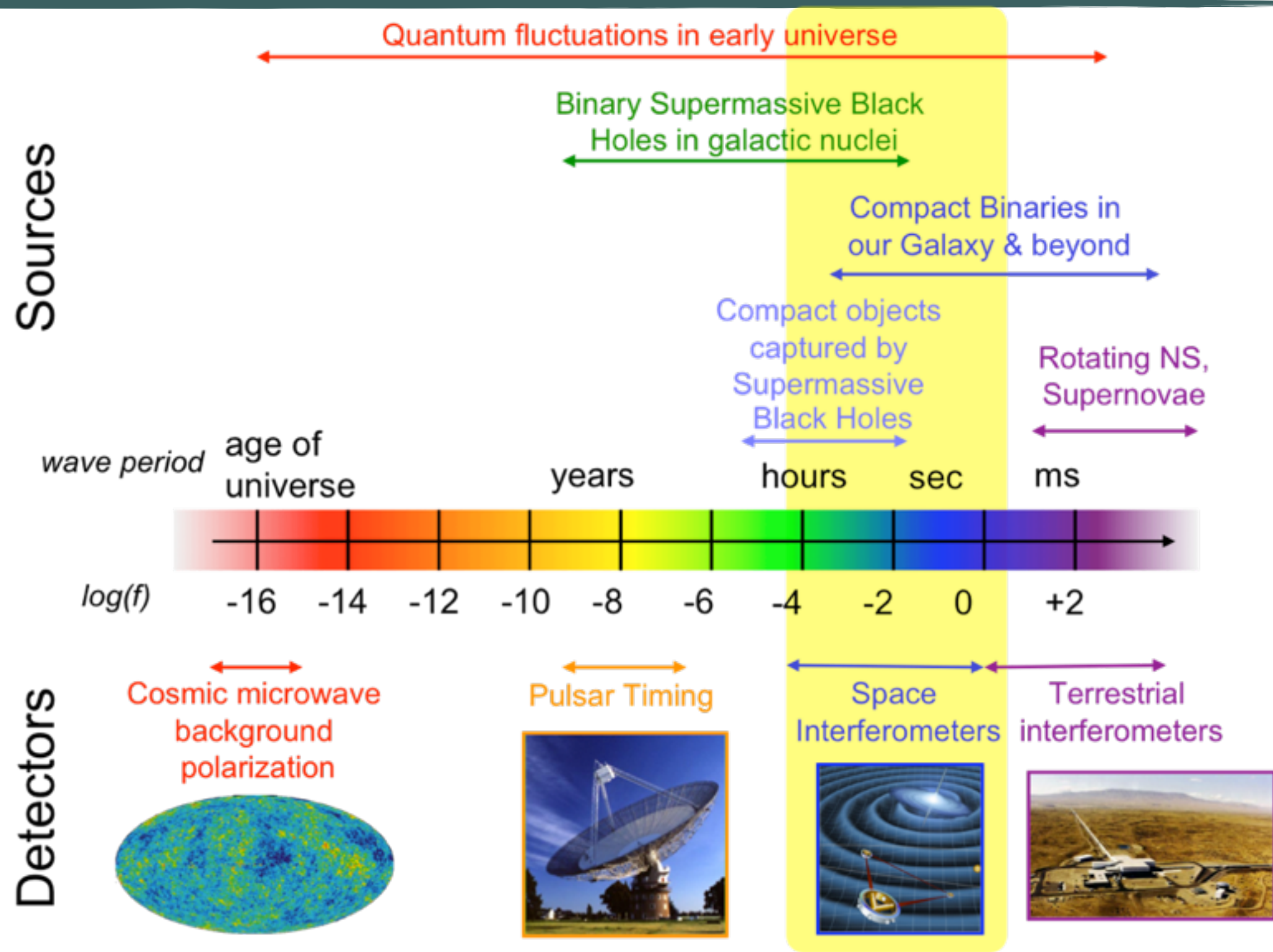
$$h \equiv \frac{\delta L}{L} \propto \frac{G^2}{c^4} \frac{1}{D} \frac{M^2}{r}$$

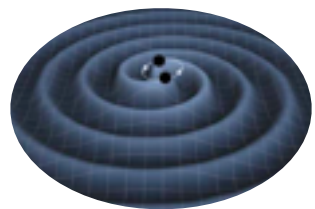


$$h \sim 10^{-21}$$

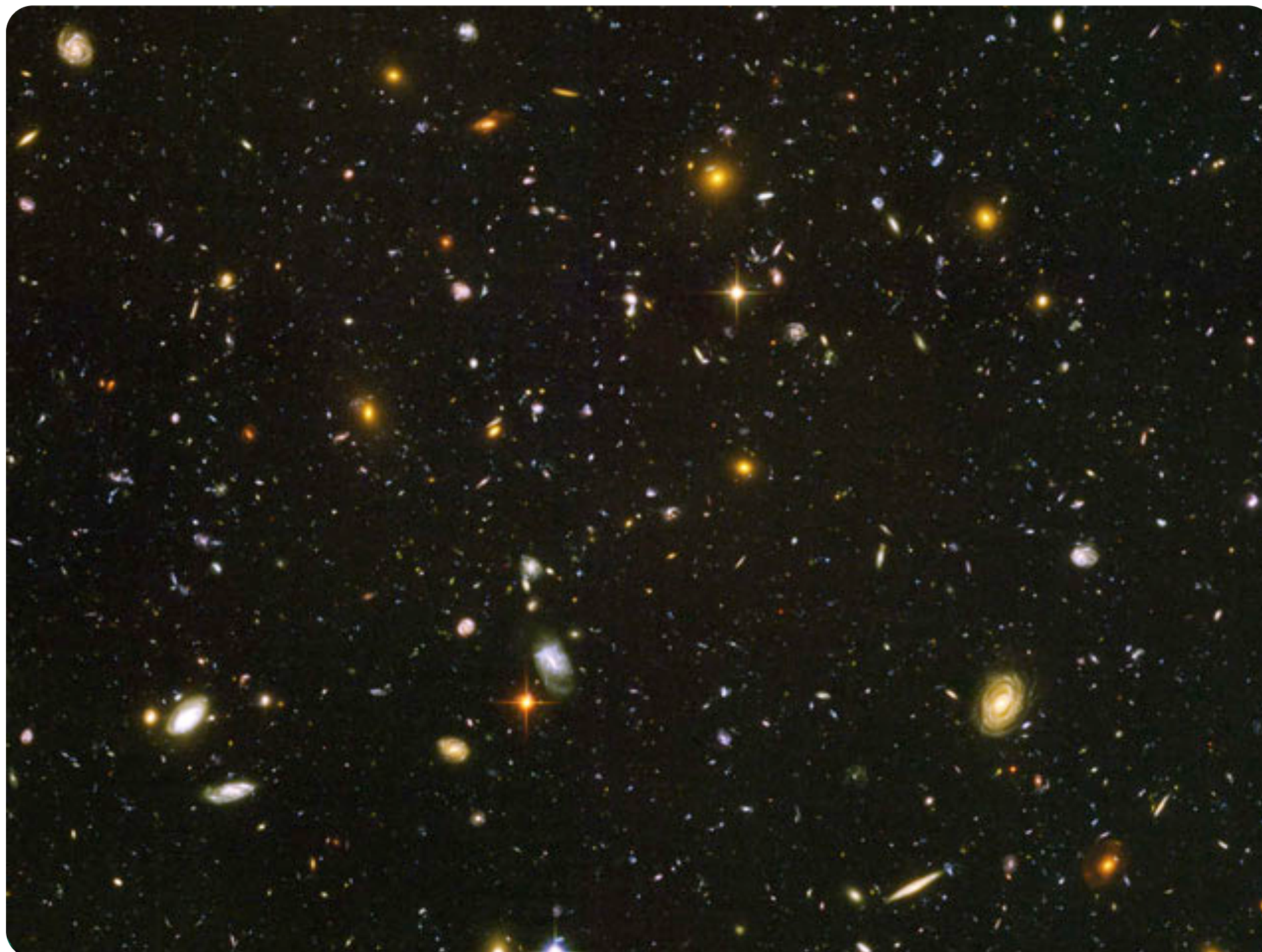


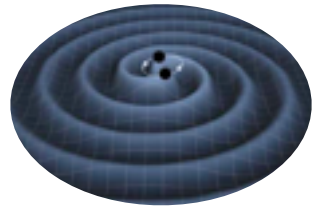
The Gravitational Wave Spectrum





Welcome to the jungle...





Seeing and Hearing the Universe

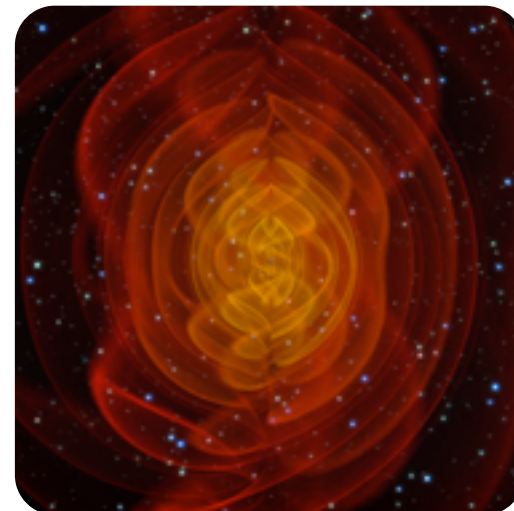
Electromagnetic Waves

- Tell us about atoms & molecules
- Often absorbed/modified in transit
- Hard to determine distance
- Easy to determine sky location
- Easy to measure redshift

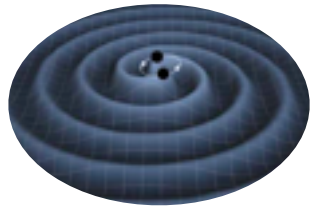


Gravitational Waves

- Tell us about (large) masses
- Travel directly to us
- Easy to determine distance
- Hard to determine sky location
- Impossible to measure redshift

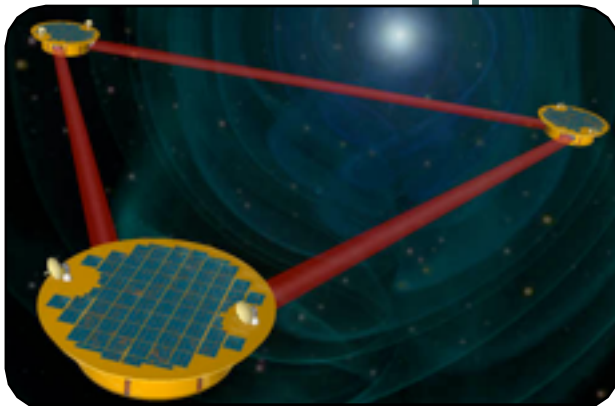


LISA



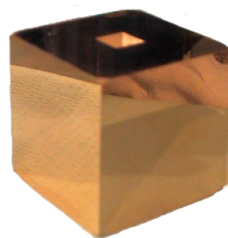
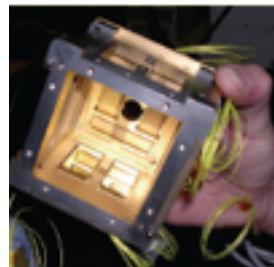
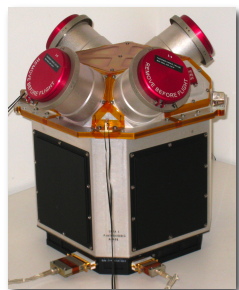
LISA Mission Concept

Triangular constellation of three identical spacecraft.



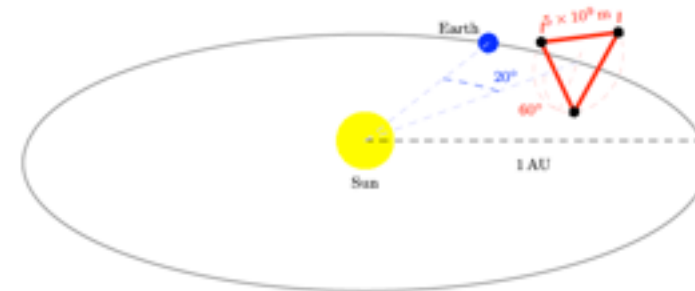
(redundancy + polarization)

Drag-free flight to realize 'freely-falling' test mass



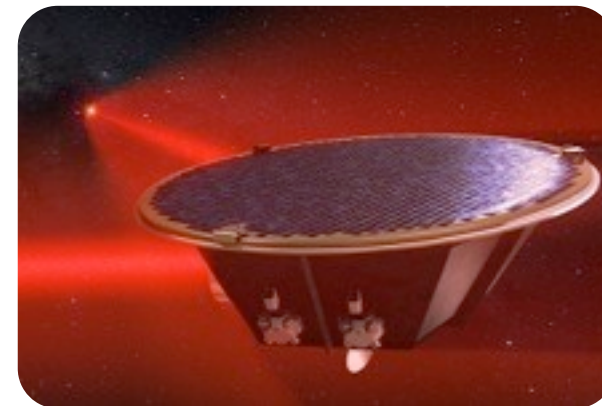
$$\delta \tilde{a} \sim 3 \text{ fm/s}^2 / \sqrt{\text{Hz}}$$

Passively-stable, Earth-trailing heliocentric orbit .



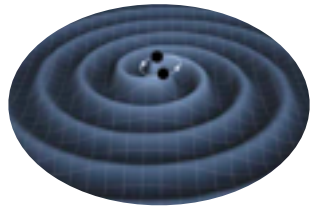
(Arm length = 5 Mkm)

Heterodyne interferometry distance measurements

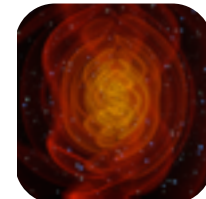
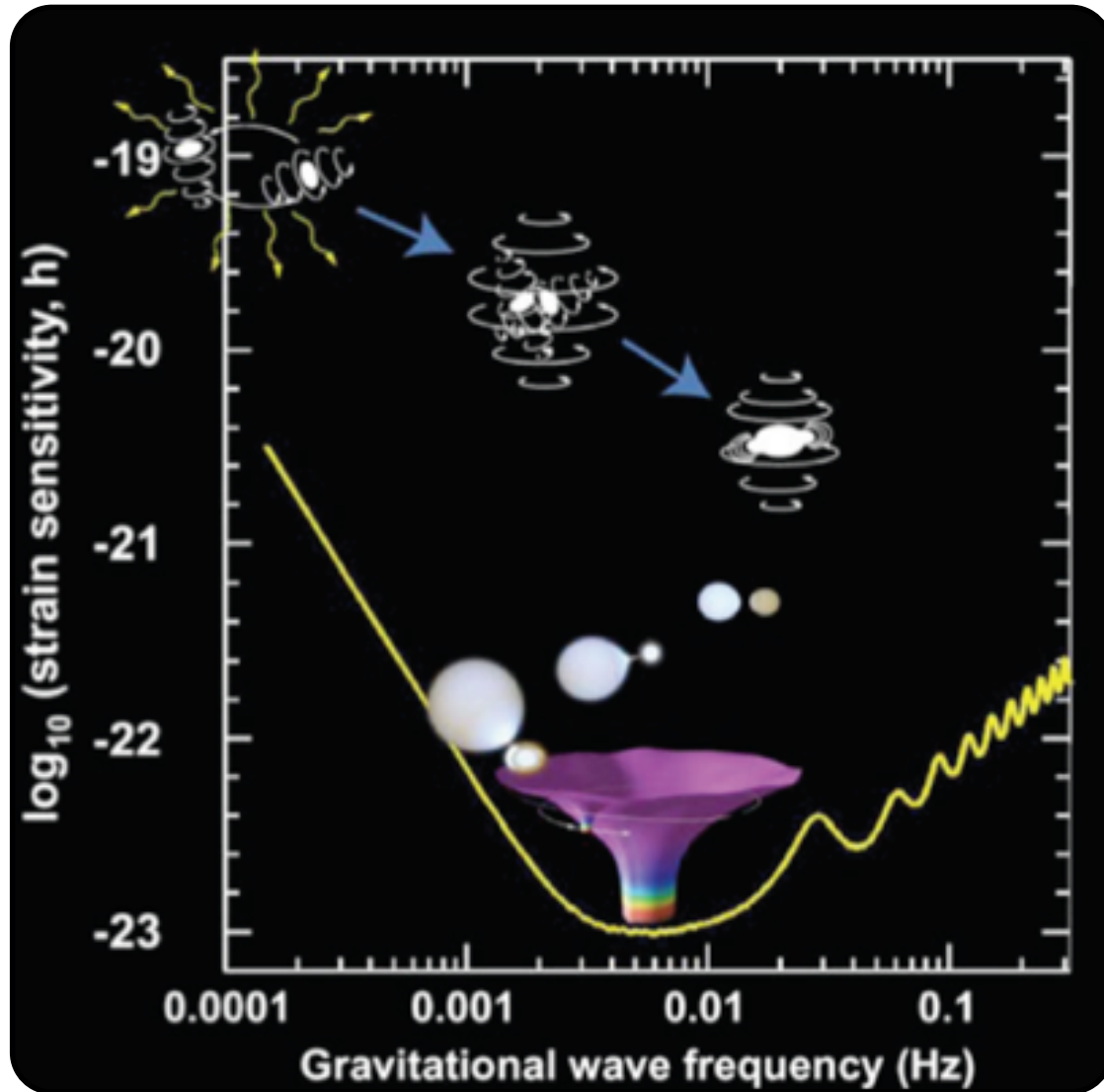


$$\delta \tilde{x} \sim 10 \text{ pm} / \sqrt{\text{Hz}}$$

LISA Science



LISA Sources



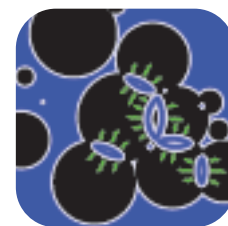
(S)MBH binaries
 $\sim 30 \text{ yr}^{-1}$



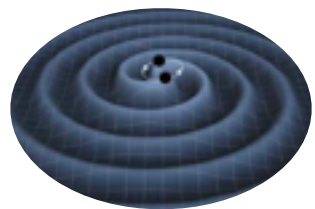
(S)MBH capture of BHs
 $\sim 10^2 \text{ yr}^{-1}$



Close binaries in Milky Way
 $\sim 10^{6-7}$ total, $\sim 10^4$ resolved



Unknowns?



Structure Formation & Galaxy Evolution

Current Picture

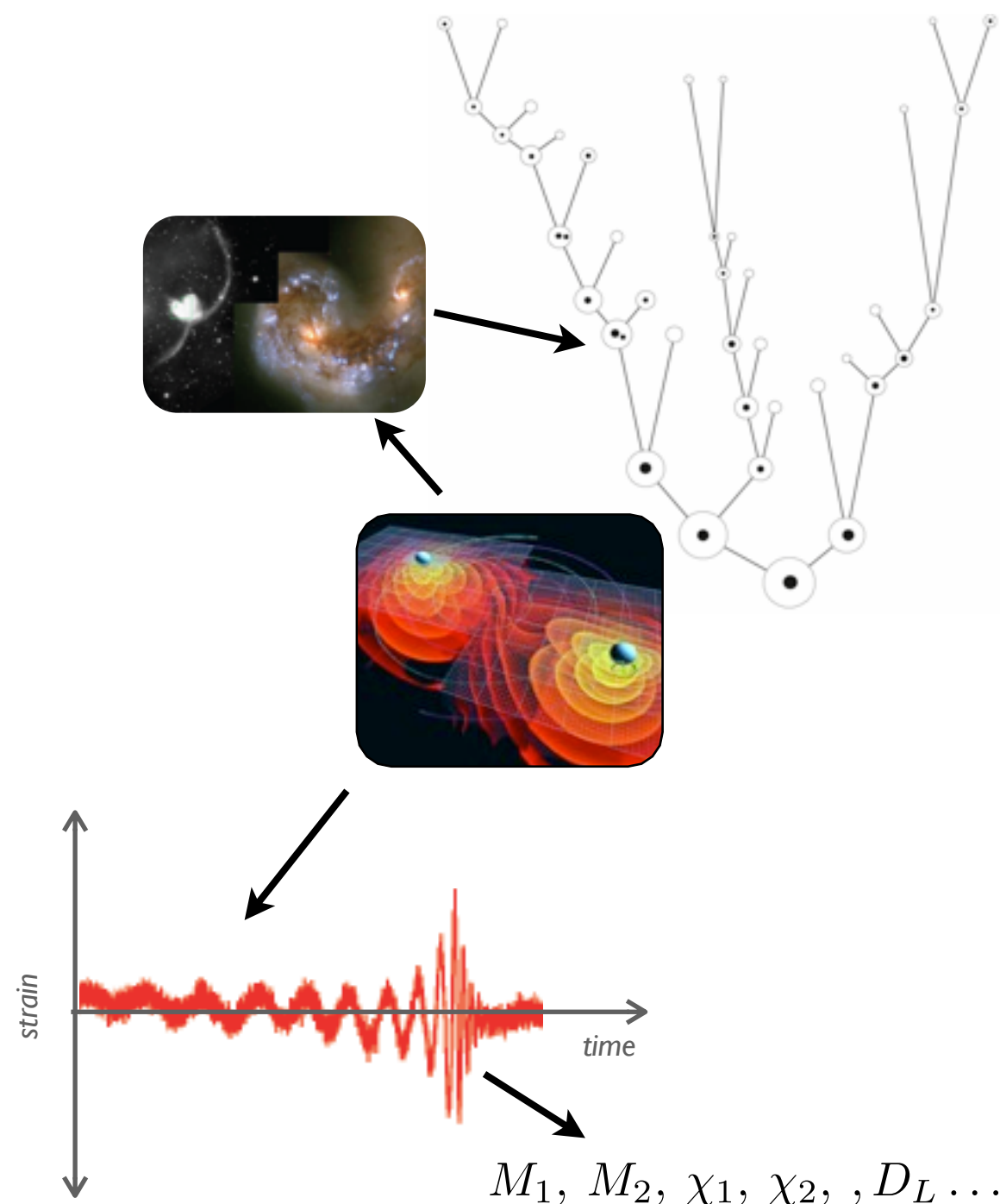
- galaxies formed hierarchically
- central black holes 'track' galaxy mass

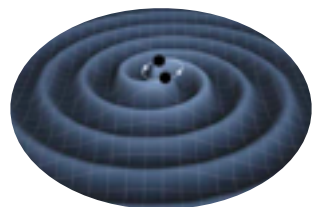
Open questions

- seed BH population
- BH growth (merger vs. accretion)
- BH merger rate ('stalled' binaries?)

GW approach

- measure statistical sample of merging binaries
- compare mass/mass ratios/spins vs. distance with model predictions





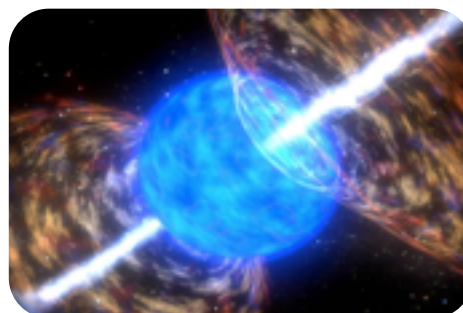
Powerful events

SN Ia



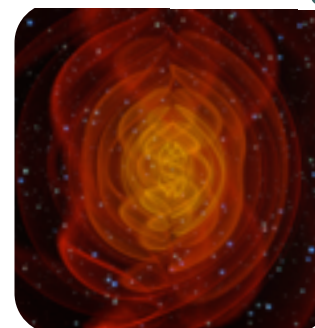
$$L_{\text{peak}} \sim 10^{43} \text{ erg/s}$$

GRB



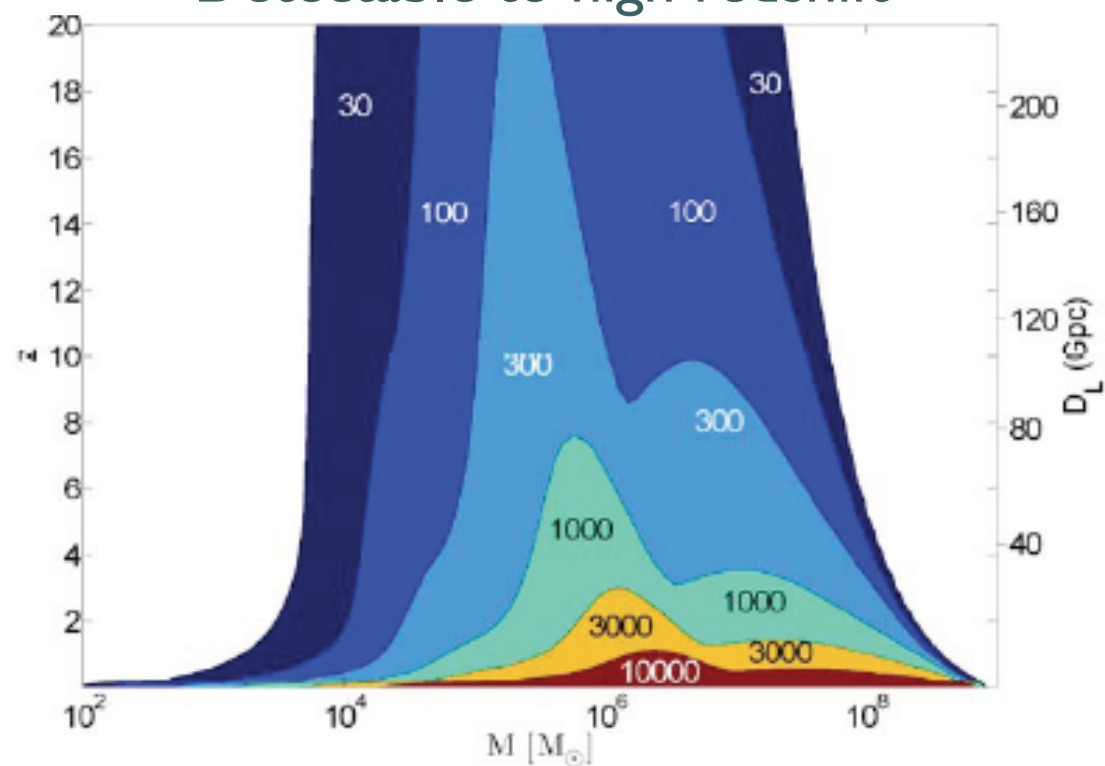
$$L_{\text{peak}} \sim 10^{53} \text{ erg/s}$$

BH-BH merger

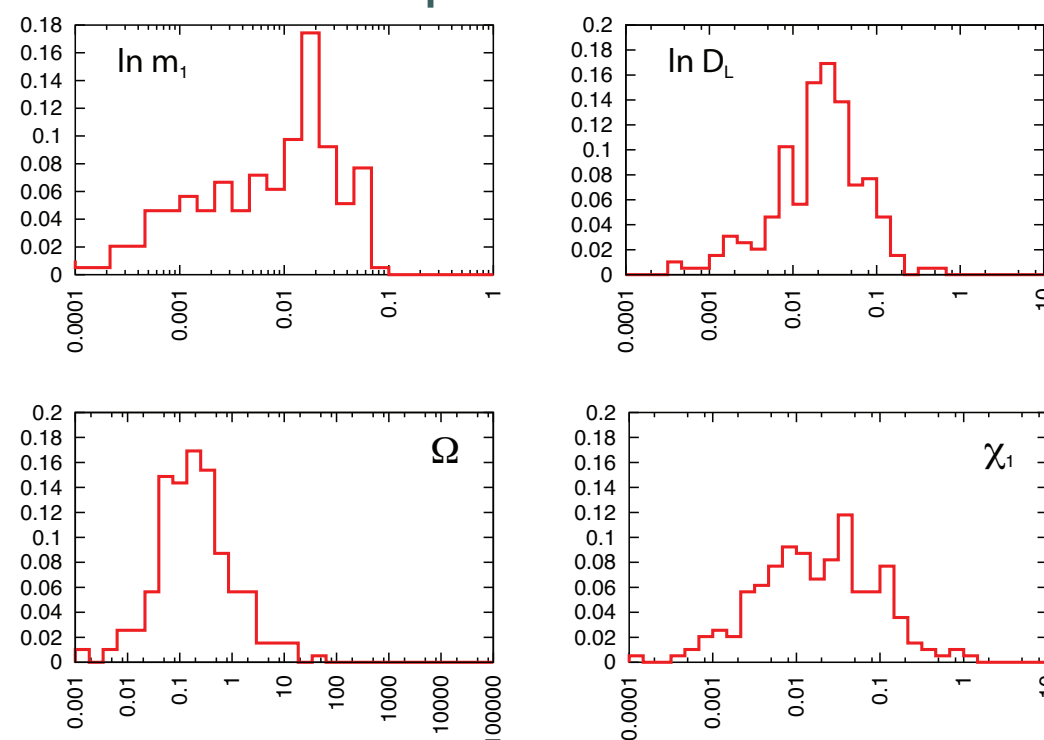


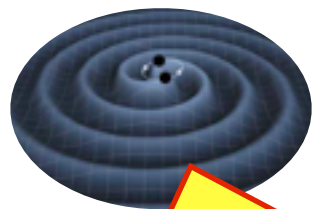
$$L_{\text{peak}} \sim 10^{56} \text{ erg/s}$$

Detectable to high redshift



Precision parameter estimation





Cosmology with 'Standard Sirens'

Multi-messenger

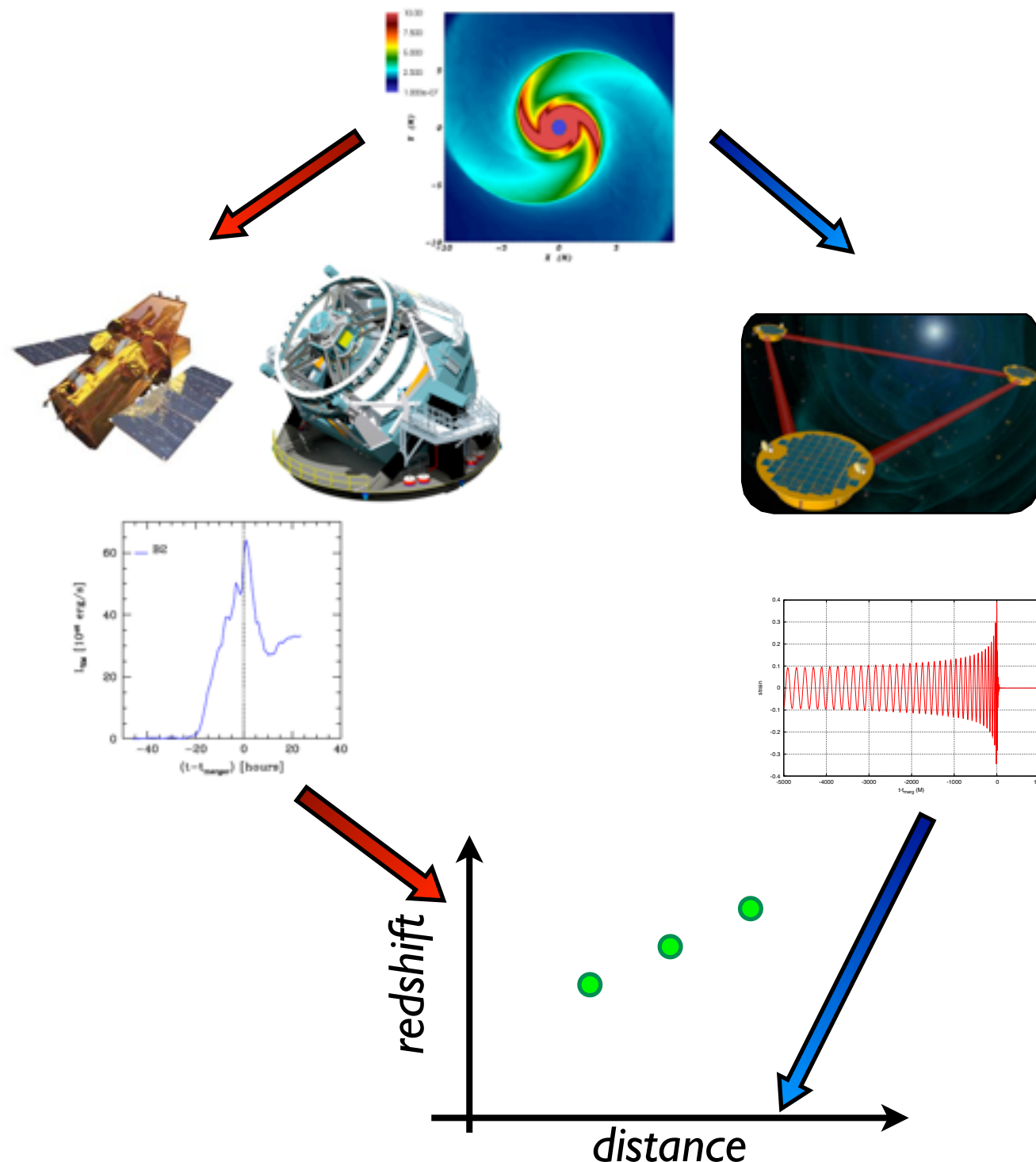
Binary merger waveform
directly encodes luminosity
distance

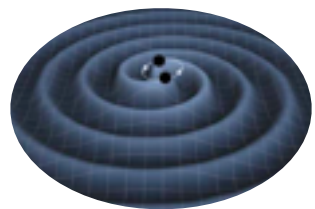
- intrinsic error $< 0.1\%$
- weak-lensing limits $\sim 3\%$

EM counterpart provides
redshift

- identify host galaxy
- 3D error box + merger time

Lower statistics but different
systematics than SN approach





Extreme Mass Ratio Inspirals

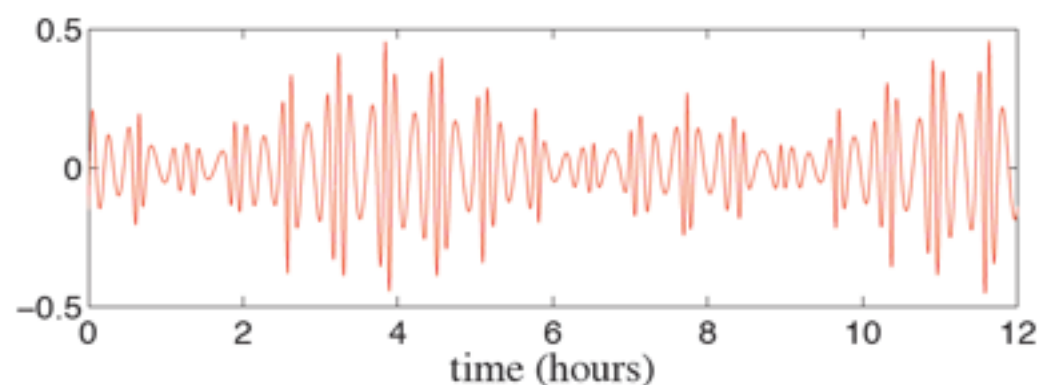
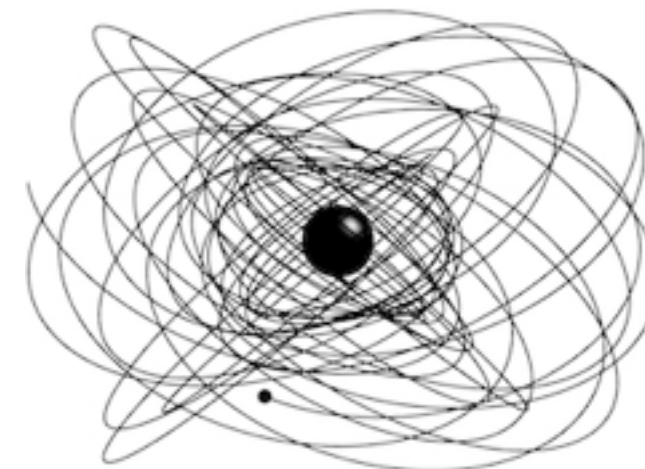
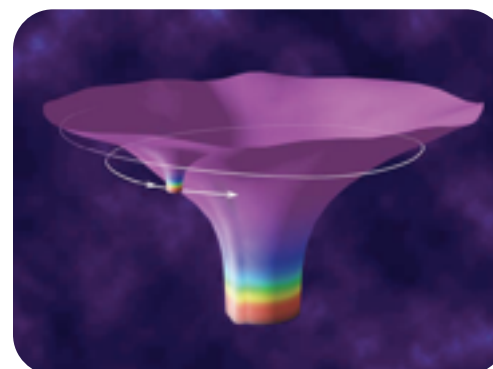
Capture of stellar-remnant BH by central BH.

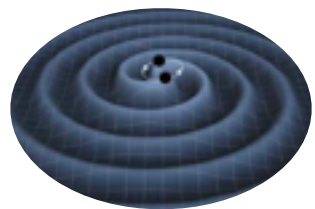
Complex, long-lived orbits

- $\sim 10^5$ cycles measured: precision parameter estimation!
- Need templates & search strategy

Tests of GR

- small BH acts as “indestructible” test particle mapping out spacetime of large BH.



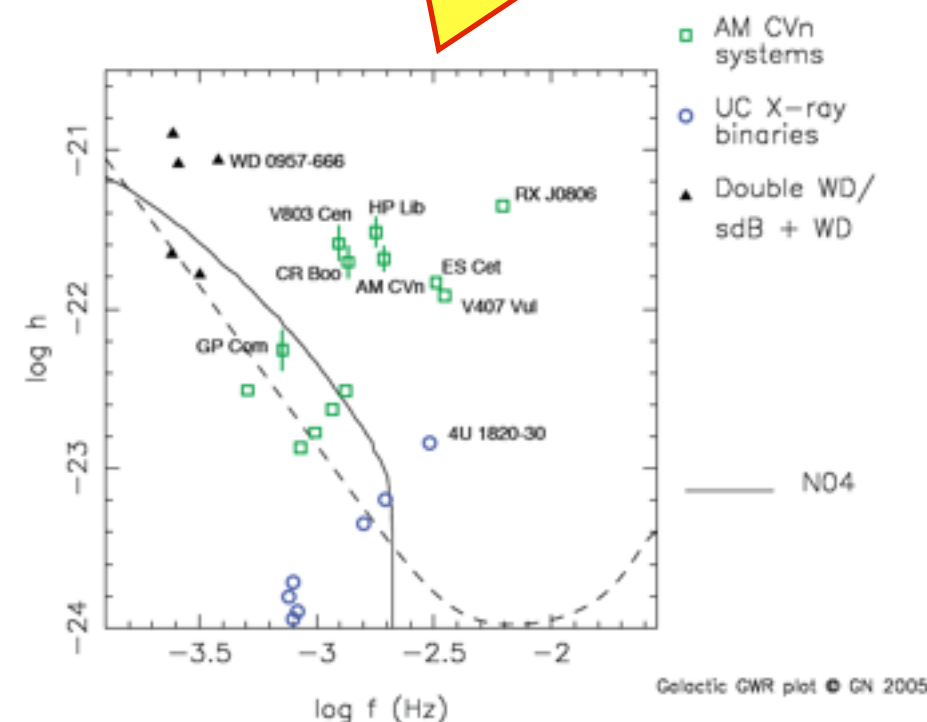


Binaries in our backyard

Multi-messenger

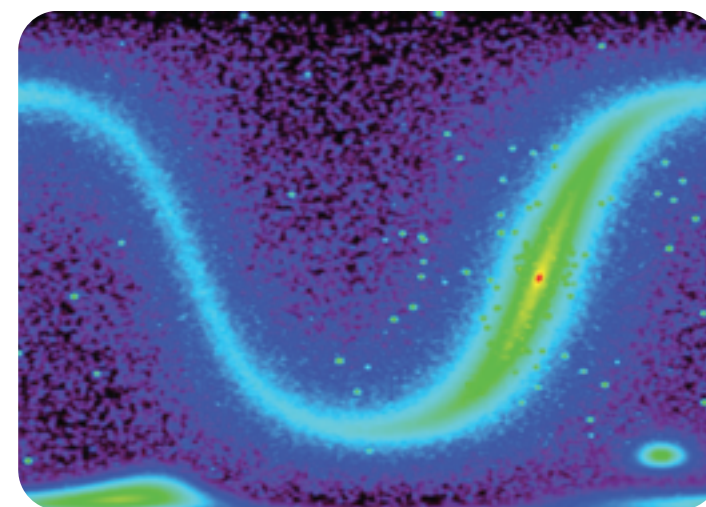
‘Ultra-compact’ binaries with WD, NS, or BH members

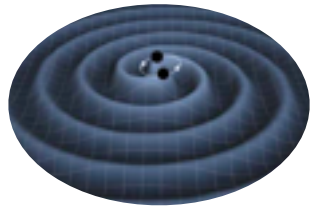
- $\sim 10^6$ in our galaxy within LISA band.
- $\sim 10^4$ resolvable
- ~ 10 already known
- Detectable in LMC, SMC and (possibly) nearby galaxies



Science applications

- compact object demographics
- binary physics (mass transfer)
- fundamental physics
- galactic structure
- globular clusters

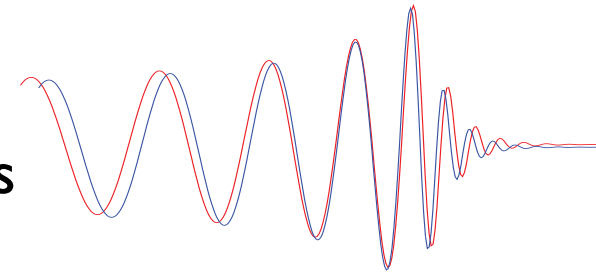




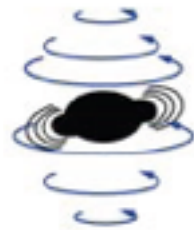
An astrophysical laboratory for gravity research

Binary (S)MBH merger

- Compare observed waveforms with templates



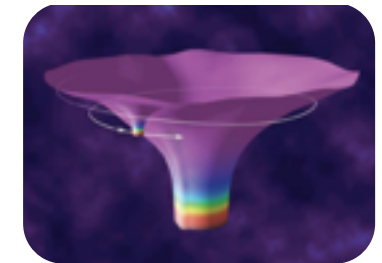
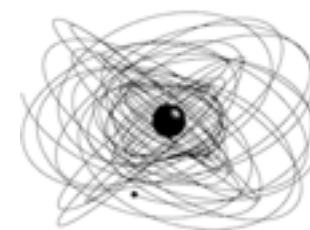
- modal analysis of ring-down



$$(M, \chi)_1 \stackrel{?}{=} (M, \chi)_2$$

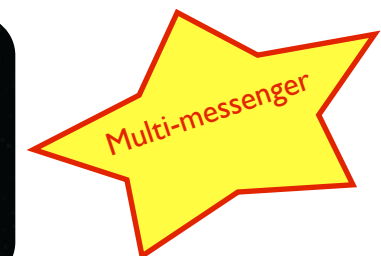
EMRIs

- Map geodesics & compare with Kerr metric

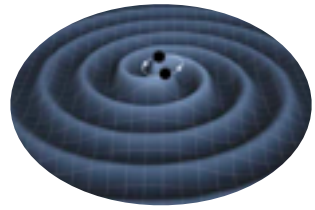


Galactic Binaries

- compare EM & GW signals to constrain graviton mass



See Living Reviews Article [arXiv:1212.5575](https://arxiv.org/abs/1212.5575) [gr-qc]



Discovery Space

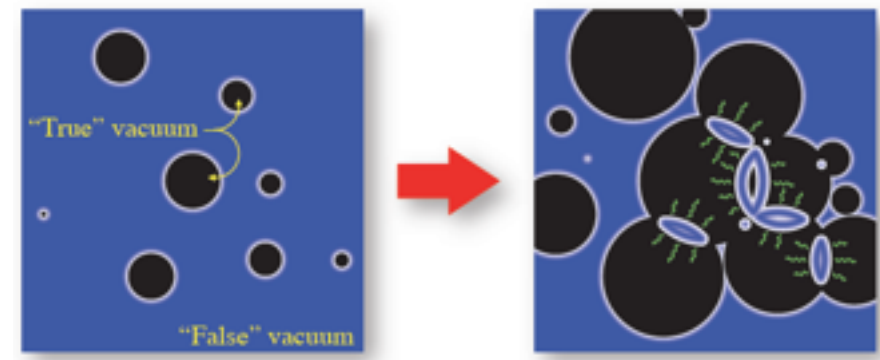
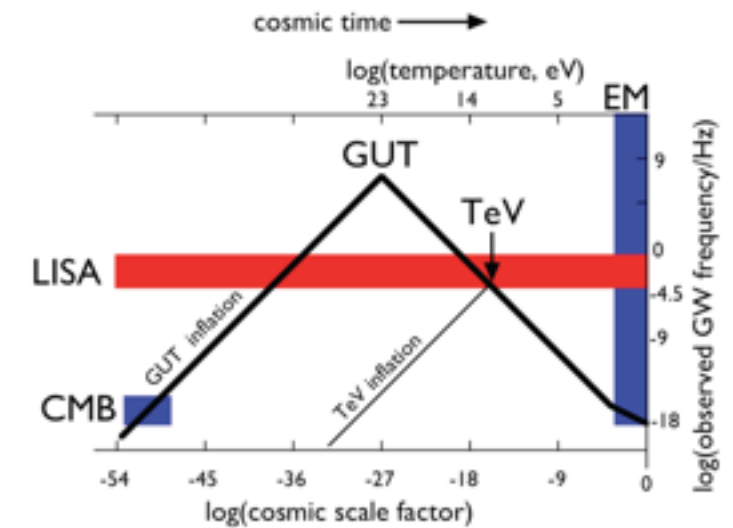
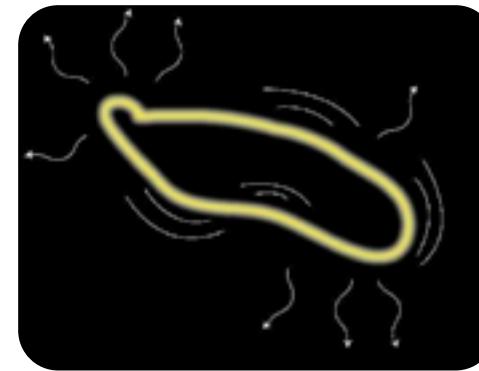
‘Exotic’ physics

- Inflation (certain models)
- cosmic strings
- vacuum bubble nucleation
- electroweak physics
- branes

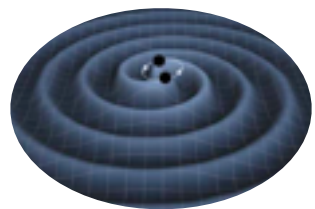
‘Exotic’ Astrophysics

- Intermediate-mass black holes

Unexpected sources

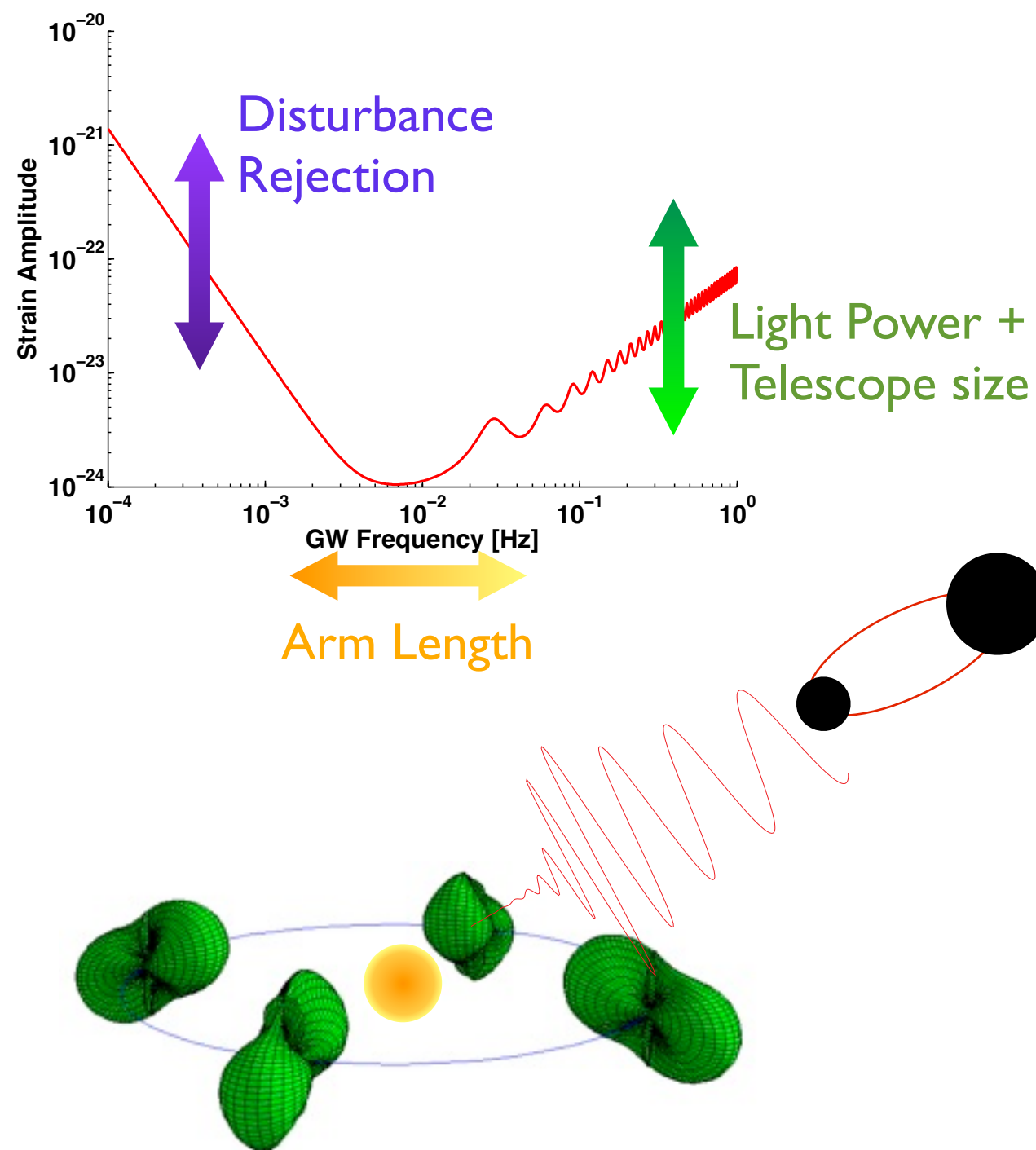


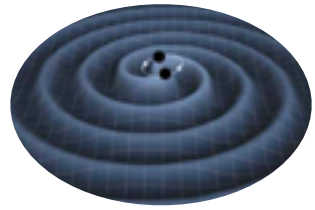
Current Landscape



Science impact of design choices

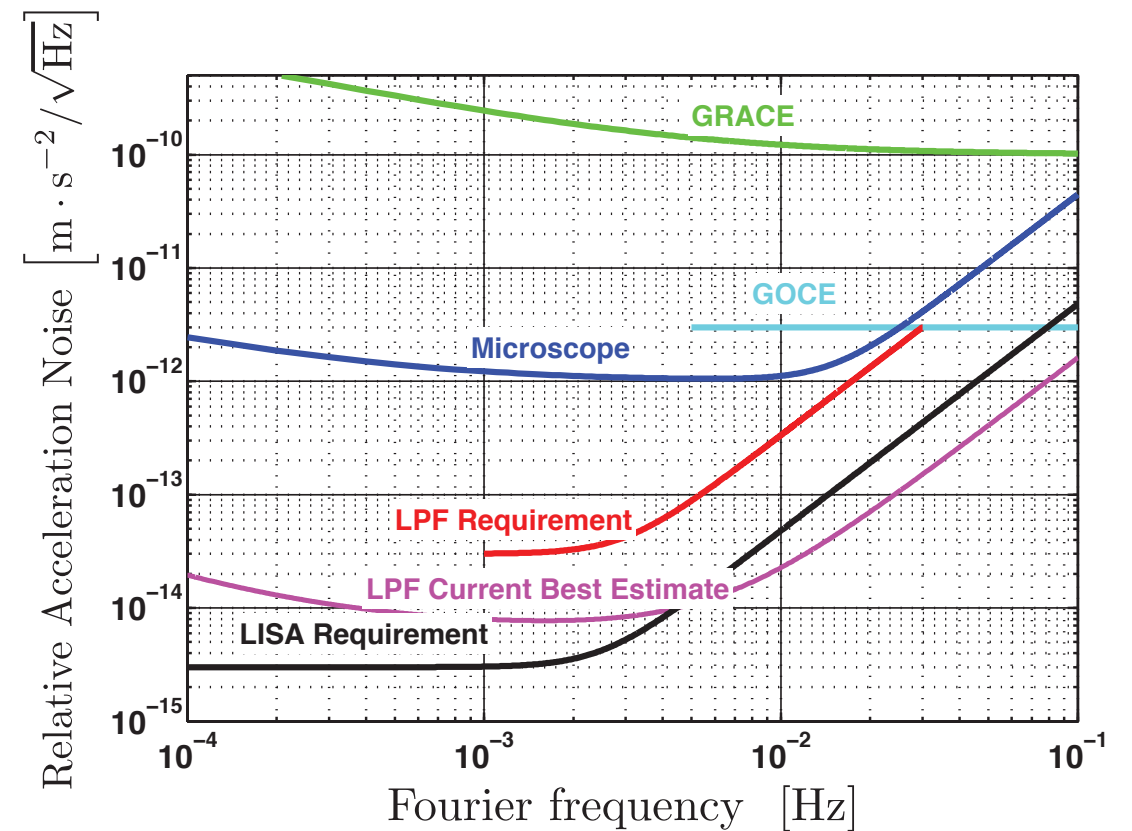
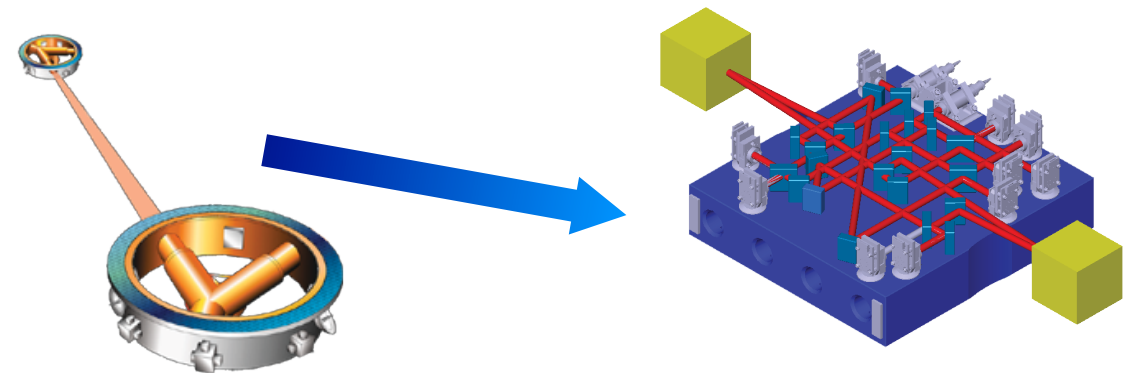
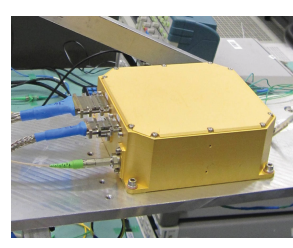
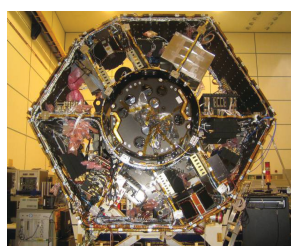
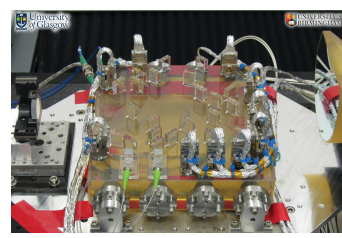
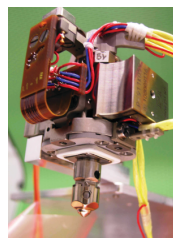
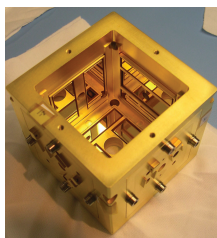
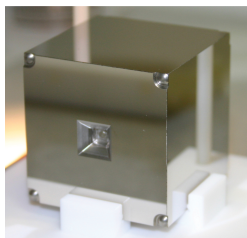
- Instrument choices affect instantaneous sensitivity (spectral response)
- Constellation configuration & orbit affect wavefront measurement (parameter estimation or 'imaging')
- Mission duration affects statistics & science associated with rare events
- Each of these affect mission cost

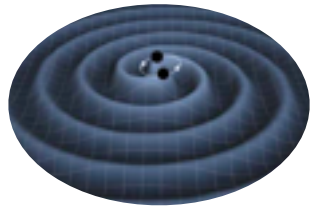




LISA Pathfinder

- Technology demonstrator for space-based GW detectors
- ESA lead, NASA-supplied thrusters & control laws
- Validate a physics-based model for disturbance reduction
- Late stages of integration & test, launch anticipated by 2015



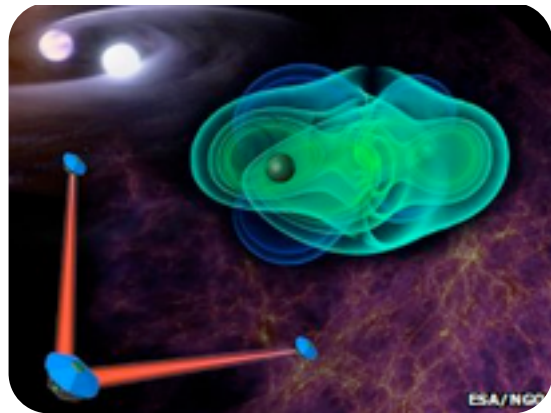


European Outlook



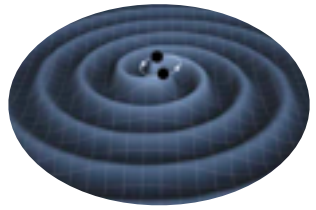
ESA call for Cosmic Visions L2 & L3 'Science Themes'

- Whitepapers due May 24th
- Theme Selection Nov. 2013
- Launches in 2028 & 2034
- International partnership at ~20%



eLISA Consortium (<http://www.elisa-ngo.org/>) organized to respond

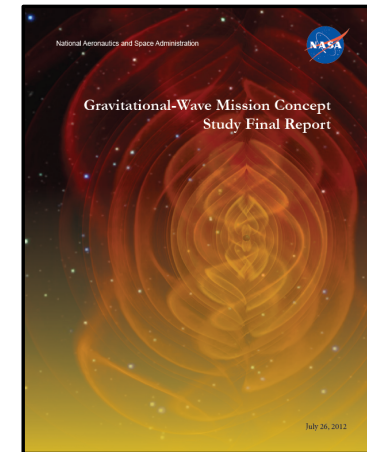
- Will use 2-arm eLISA/NGO concept as strawman for whitepapers
- Refining science case
- Negotiating national roles & responsibilities
- Pursuing technology development



US outlook

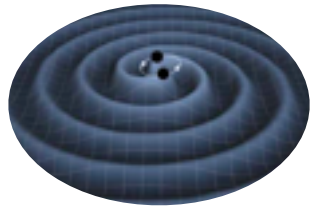
2011-2012 NASA Mission Concept Study

- Explore trade space of science, cost, and risk
- community input + analysis + synthesis
- final report (<http://pcos.gsfc.nasa.gov>) in August 2012
- Findings (my interpretation):
 - LISA-like missions have an appropriate balance of science, cost, and risk
 - viable missions are all over ~\$1B



Opportunities

- Minority partner in European mission
- Facility class mission (w/ or w/o partners) in the next decade
- Need to prepare *science and technology* for both possibilities



It's a Long Road...

2016?



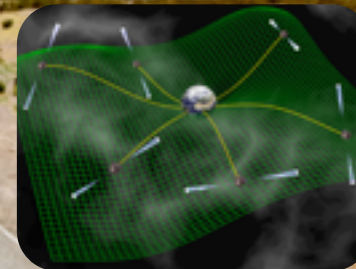
Ground-based detectors

2028?



space-based
detectors

2020?



pulsar timing
arrays

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